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Designing a hedgerow network in a multifunctional agricultural landscape: Balancing trade-offs among ecological quality, landscape character and implementation costs

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ABSTRACT

Spatial planning aimed at multifunctional agriculture can be seen as a negotiation process on environmental, social and economic aspects of land use. Complexity arises due to the high number of stakeholders and due to the limited knowledge, which is often organized along disciplinary divides. This paper sets out from the premise that the role of agronomy in such land use planning processes can be strengthened by approaches that allow multi-objective and multi-scale evaluation of spatially explicit land use alternatives. We present an application of the explorative Landscape IMAGES framework, which employs the Differential Evolution optimization strategy and the concepts of Pareto optimality that are relatively easy to implement and to combine with spatially explicit indicator assessments. This technique yields a set of solutions, each representing a spatial configuration of hedgerows in a landscape along with the performance of the landscape in terms of Pareto rank and efficiency. The methodology was applied in a redesign of the structure of linear landscape elements in an agri-ecological zone in The Netherlands where 7 indicators representing ecological quality, landscape character and implementation costs were considered. The case study was developed in interaction with an NGO involved in landscape management planning and implementation.

Spatial cohesion in the landscape was found to increase with larger total hedgerow length, but could also be improved without increasing the total length (and therefore costs of establishment and maintenance). Trade-offs existed with other objectives, since this change would involve replacing hedgerows currently positioned in the longitudinal direction (*L*) of the fields by hedgerows in the transversal direction (*T*). This change would compromise cultural heritage value as expressed in the *L*/*T* ratio, and it would require removal of mature hedgerows in some places and adding of new hedgerows elsewhere in the landscape, thereby increasing implementation costs.

The approach was evaluated positively in terms of design validity, output validity and end-user validity. The role of the Landscape IMAGES framework in setting a research agenda to enhance the role of agronomy in multifunctional land use planning is discussed.

1. Introduction

Diversification of farming systems as an answer to the sustainability problems in agriculture and to the increasing urbanization of Europe has given rise to new economic on-farm activities such as nature conservation, agro-tourism and maintenance of cultural heritage values (Vos and Meekes, 1999; O'Conner et al., 2006). Different from the traditional agricultural activities of food and fibre production these activities can not be managed at a farm or field scale alone, but also require to be managed at a regional scale (Gottfried et al., 1996; Cumming et al., 2006). To realize the potential of these new economic activities farmers increasingly need to interact with other stakeholders in the region as part of regional planning processes (Holloway et al., 2006; Franks and Mc Gloin, 2007). This has consequences for agronomic research which thus far has had only limited attention for the regional scale (e.g. Leenhardt et al., 2009).

Spatial planning of land-use and management activities aimed at sustainable natural resource management may be seen as a complex negotiation process on environmental, economic and social aspects of land-use. Complexity arises due to the high number of stakeholders with often contrasting perspectives and divergent expectations about future development of a region (Kangas et al.,

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2005) and the limited scientific understanding of biological processes (Carpenter et al., 2006).

In negotiation situations, a widely applied planning method is the construction of "sketch designs" for regional development based on narrative scenarios describing drivers of change for the future and normative viewpoints on development objectives and the indicators by which these are to be measured (Münier et al., 2004; Dockerty et al., 2006). Because of their basis in narratives, sketch designs are necessarily few in number, e.g. representing business as usual and responses to 2–4 extreme future scenarios. The use of a small number of alternative sketch designs may seem attractive in complex planning processes since it avoids the 'agony of choice', but at the same time this approach does not allow to explore plans in which objectives would be better served by overcoming trade-offs among objectives.

In contrast to the planning practice of sketch designs, scientific efforts to support decision making start from a much broader set of possible options, but in their results usually emphasize single solutions, which are denoted as 'optimal' in methods such as mathematical programming or multi-criteria approaches, or 'acceptable' in the case of methods such as viability analysis or constraint programming (Groot et al., 2009). Although these methods may provide valuable insights, there is no systematic exploration of the solution space. As a consequence, these methods fail to clarify the interactions between the environmental, economic and social indicators and present a narrow view of future possibilities, addressing only a limited number of perspectives (Carpenter et al., 2006).

In addition to the methodologies used, the traditional separation of agronomy from other disciplines involved in land-use is cause for concern when comparing the actual and the potential role of agronomic knowledge in land-use planning negotiations. A review by Rossing et al. (2007) not only demonstrated the strength of studies from agricultural sciences in addressing indicators in the economic and abiotic environmental domains, but also revealed a lack of attention for the social and biotic environmental domains. The IAASTD report (IAASTD, 2008) came to similar conclusions, based on a worldwide assessment of agricultural knowledge. A recent review by Leenhardt et al. (2009), albeit strongly focused on French studies, showed that agronomic studies at the regional scale addressed particularly agriculture-to-agriculture effects, e.g. through gene flow, water availability or erosion, or pollutant effects of agriculture through plant nutrients and pesticides.

There is a rapidly increasing body of literature on the analysis and exploration of multifunctionality in land-use systems (Renting et al., 2009; Groot et al., 2009; reviews by Otte et al., 2007 and Rossing et al., 2007). These research efforts have resulted in the development of a number of methods for spatial and dynamic planning for natural resource management in multifunctional agricultural landscapes (e.g. Swetnam et al., 2005; Hajkowicz et al., 2005; Hölzkamper and Seppelt, 2007; Groot et al., 2007; Tichit et al., 2007; Bryan and Crossman, 2008). This paper departs from the premise that supporting the adjustment of agriculture to new multifunctional demands of society requires methodology for salient interaction with the broad community involved in regional planning. In a previous paper (Groot et al., 2007), we described the conceptual basis of an approach called Landscape IMAGES in which economic objectives could be addressed along with abiotic and biotic environmental objectives. In this paper we describe an application of the approach to a real-world case study which allowed us to explore the validity of the approach in terms of design, output and end-users (Bockstaller and Girardin, 2003), and identify the research agenda for input of knowledge from agronomy.

The Landscape IMAGES methodology entails the exploration of the whole solution space to find the trade-offs or the optimal pattern of interactions between the land-use functions (Chee, 2004). Any Landscape IMAGES implementation consists of two or more objectives, decision variables which are spatially explicit and often integer, indicators to evaluate the performance of solutions, constraints including those on objectives or decision variables, and a vector-based landscape map in GIS which describes the spatial relations in alternative solutions and allows model results to be visualized. Key to the identification of trade-offs among objectives is the use of Pareto-optimality to assess the quality of a solution in comparison with other solutions found.

The application presented in this paper concerns the redesign of a hedgerow network in an agri-ecological zone in The Netherlands. The case describes an interactive model-development process with a non-governmental landscape management organization responsible for planning and realization of adjustments in the landscape structure of agri-ecological zones in the province of Friesland, The Netherlands. In the Dutch planning system adjustments on private land can only be made with the consent of land owners, in this case farmers. Proposed changes to landscape structure have long-term repercussions for agricultural practice by limiting the space to manoeuvre with machinery and by requiring the farmers to maintain hedgerows, payment of which is a political issue and uncertain. These topics are highly contentious in the region where the farmers aim to practice 'large scale farming in a small scale landscape'. As in their restructuring projects the landscape management organization depends on collaboration of farmers, insight in alternative plans which would be acceptable to all parties was deemed to be useful. In the next section we present the Landscape IMAGES framework and its application to the design issues in the case study. Results are presented (Section 3) and discussed (Section 4) with a particular focus on the validity of the approach and the niche the approach provides for agronomy to take its place in spatial planning processes.

2. Methodology

2.1. Conceptual model

The exploration of the trade-offs between performance criteria or objectives can be formulated as a multi-objective design problem, which can be generally stated as follows.

$$\text{Max}\, F(x) = (F_1(x), \ldots, F_y(x))^T \quad (1)$$

$$x = (x_1, \ldots, x_z)^T \quad (2)$$

Subject to i constraints:

$$g_i(x) \leq h_i \quad (3)$$

where $F_1(x), \ldots, F_y(x)$ are the y objective functions that are simultaneously maximized or minimized, and $(x_1, \ldots, x_z)$ are the decision variables that represent the activities allocated to the z spatial units. The decision variables can assume values from a predefined array $x \in S$, where S is the parameter space. Constraints (Eq. (3)) may arise from the problem formulation, for instance by limitations on the inputs or outputs related to farming or management activities.

2.2. Pareto-based Differential Evolution

The trade-offs between the objectives were explored with a multi-objective implementation of the evolutionary strategy of Differential Evolution (DE) developed by Storn and Price (1997). Currently, DE is widely used in the research community due to its simplicity, efficiency and robustness (Bergey and Ragsdale, 2005; Mayer et al., 2005). DE involves the iterative improvement of a set of solutions or genotypes, consisting of alleles. In our application the genotypes represent alternative landscapes and the alleles are

decision variables in which the occupation of the field borders was encoded as a real number. A genotype is a multi-dimensional vector $p = (p_1, \ldots, p_z)^T$ of z alleles. Each allele p_i is initialized as $p_{i,0}$ by assigning a random number within the allowed range:

$$p_{i,0} = L(p_i) + r_i\,(U(p_i) - L(p_i)) \tag{4}$$

where r_i denotes a uniformly distributed random value within the range [0, 1] and L and U are the lower and upper values of the allowed range. A new generation $t+1$ is created by applying mutation and selection operators on the individuals in the population P of the current generation t. The first step of the reproduction process is generation of a trial population P' that contains a counterpart for each individual in P, produced by parameterized uniform crossover of a target vector and a mutation vector. The mutation vector is derived from three mutually different competitors c_1, c_2 and c_3 that are randomly selected from the population P in the current generation t. The allele values are taken from the mutation vector with probability C_R:

$$p'_{i,t+1} = \begin{cases} c_{3,i} + F \times (c_{1,i} - c_{2,i}) & \text{if } r_i < C_R \\ p_{i,t} & \text{otherwise} \end{cases} \tag{5}$$

where r_i is a uniformly distributed random variable. The parameter $F \in [0, 2]$ is a parameter that controls the amplification of differential variations. After a mutation, the value of $p'_{i,t+1}$ can extend outside of the allowed range of the search space. For allele values that violate the boundary constraints the repair rule presented in Eq. (6) is applied. This rule implements a mechanism that can be denoted as 'back folding': the adjustment for the allele is calculated by interpolation into the allowed range from the boundary by a value that is proportional to the difference between the boundary and violation values:

$$p'_{i,t+1} = \begin{cases} L(p_i) - \dfrac{p'_{i,t+1} - L(p_i)}{F} & \text{if } p'_{i,t+1} < L(p_i) \\ U(p_i) - \dfrac{p'_{i,t+1} - U(p_i)}{F} & \text{if } p'_{i,t+1} > U(p_i) \\ p'_{i,t+1} & \text{otherwise} \end{cases} \tag{6}$$

A trial genotype p'_{t+1} replaces p_t if it outperforms the parent genotype. Here, better performance is interpreted as a better Pareto ranking, a higher Pareto efficiency or located in a less crowded area of the solution space than the parent genotype. These performance criteria are explained below. Population size N is determined by the number of alleles in the genotype z and a multiplication factor M. The last parameter in the DE algorithm is the number of generations G, which serves as the stopping criterion. The parameter values for F, C_R, M and G as employed in this study were derived from factorial analysis in preliminary optimization runs, where G was chosen such that the volume of the solution space no longer expanded.

The concept of Pareto optimality was used to assess the performance of solutions, since it avoids the need of normalization and a priori weighing of objectives as is the case with common multi-criteria methods. As such it fits very well the aim of supporting negotiation by providing insight in objectives without undue a priori restriction of the solution space.

The first criterion for the performance of a solution is its Pareto rank as proposed by Goldberg (1989). Individuals in the population are Pareto-optimal when they do not perform worse than any other individual for all the objectives, i.e. when they perform equal to or better than any other individual in at least one objective. In such case, there is no objective basis to discard the individual. These individuals are called non-dominated and receive rank 1 (Fig. 1). This set of solutions is called the trade-off frontier. The next step in Pareto-ranking the entire population of solutions is to remove the rank 1 individuals from the population and identify a new set of non-dominated individuals, which is assigned rank 2. This process is continued until all individuals in the population are assigned a Pareto rank.

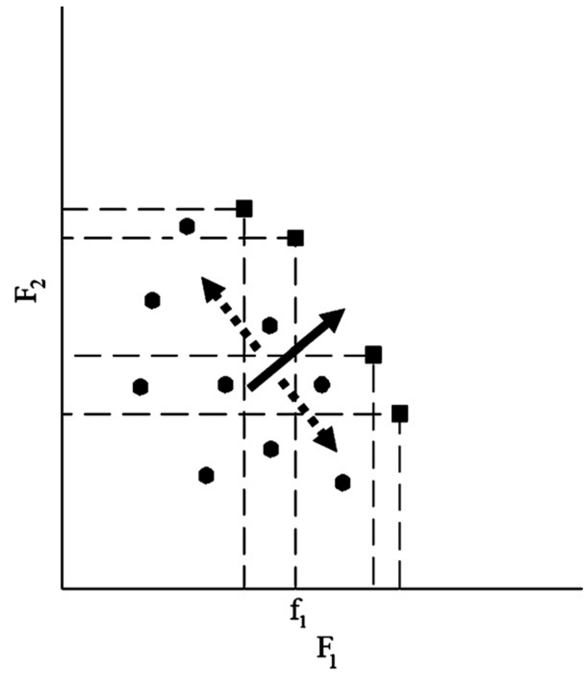

Fig. 1. Pareto optimality illustrated for a solution space of two objectives F_1 and F_2 that are maximized: symbol (■) indicates solutions which are not dominated by any other solutions: setting level f_1 for objective function F_1 as a minimum level, there will be no alternative solution in the dataset with a higher value for objective F_2. The arrows indicate the selection pressure exerted by Pareto ranking (solid) and the crowding metric (dashed).

The probability of equal Pareto ranks increases when the number of dimensions of the solution space increases, i.e. when the number of objectives in the decision problem increases. This means that the number of solutions in the trade-off frontier increases, which causes the DE algorithm to progress more slowly towards better solutions. Das (1999) proposed to take Pareto efficiency as an additional performance criterion in the case that two solutions have Pareto rank 1. A solution is Pareto efficient of order k if it is not dominated by any other solution in each k-dimensional subset of the y-dimensional solution space (Das, 1999), where $1 \le k \le y$ and y is the number of objectives. Solutions with a low Pareto efficiency value are considered better compromise solutions since they are dominated in fewer dimensions. The concept of Pareto efficiency can be seen as an extension of the concept Pareto optimality.

If two solutions have the same rank and efficiency, a third selection criterion, the crowding distance, is taken into account. The metric Θ represents the within-rank solution density and is calculated from the normalized distance from solution p to the nearest solution in the search space, as follows (Deb et al., 2002):

$$\theta = \sum_{j=1}^{k} \frac{|d_i - \bar{d}|}{|B_j|} \tag{7}$$

where B_j is the range of objective j, which is calculated as the difference between the minimum and maximum values of objective j. Variable d_i denotes the Euclidian distance between genotype p and the nearest neighbouring solution within the Pareto front of a given rank and the parameter $\bar{d}$ is the average of these distances. An individual is replaced by a trial solution of the same rank and efficiency if the latter is located in a less densely populated part of the solution space. Pareto ranking exerts a pressure orthogonal to the surface of the trade-off frontier, whereas the crowding metric stimulates spread of solutions over the surface and within the

solution space (see arrows in Fig. 1). Together these metrics ensure progress of the entire frontier to better solutions.

2.3. Hedgerows in the Friesian Woodlands

The Friesian Woodlands are a unique agricultural area in the north of The Netherlands consisting of a mosaic of fields bordered by hedgerows. The landscape of the Friesian Woodlands is comparable to the Bocage landscapes in Brittany and Normandy (Baudry et al., 2001) and contains the densest hedgerow networks of The Netherlands (Dijkstra et al., 2003). The hedgerows were originally planted as cattle fence and property boundary, but are nowadays highly valued for their ecological and cultural-historical qualities (De Boer, 2003). The prevailing land-use activity between the hedgerows is dairy farming. On some farms a limited proportion of up to 5% of the area is used for forage maize production, while the rest of the area is occupied by permanent grassland. In this setting the Landscape IMAGES framework has been applied to support the development of an agro-ecological zone of 873 ha by evaluating and generating alternatives for a sketch design produced by a regional, non-governmental landscape management organization 'Landschapsbeheer Friesland' (LBF) responsible for development and implementation of landscape improvement projects in the zone. A set of alternative landscape configurations was generated with the Pareto-based Differential Evolution multi-objective optimization algorithm, in which each solution represented a different configuration of hedgerows in the case study area. The results of the optimizations were compared with the performance of the 'original' hedgerow configuration as encountered by LBF at the start of the planning project, and the implemented 'sketch design' as developed and implemented by the landscape management organization.

2.4. Objectives and indicators

Objectives and indicators for the Landscape IMAGES application were developed in an iterative process of model design, demonstration of consequences and redesign of the model between the researchers and LBF, in which the representatives of LBF played an active role in the formulation of objectives and indicators. In the course of three meetings a set of objectives and indicators initially proposed by the researchers was adjusted and extended to match the interests of LBF. The final set included a total of 7 indicators describing ecological quality, landscape character, and costs of implementation and maintenance.

2.4.1. Ecological quality

Spatial coherence of the hedgerow network was used as a measure for ecological quality. Depending on their mobility different species will experience a different degree of clustering of hedgerow habitat in the network. The connectivity of landscapes can be calculated from the relation between dispersal capacity (D_{cap}) of the species and the size of the largest interconnected cluster of habitat in the network (Urban and Keitt, 2001; Fall et al., 2007). In the case study the integral of this function (Fig. 2a) was used as measure of spatial coherence and was maximized.

The relation between dispersal capacity and maximum cluster size can be calculated efficiently by determining critical distances in the network structure using graph theory (Bondy and Murty, 1977). The critical distance is the smallest non-habitat distance between two parts of the network that needs to be crossed in order to be able to connect these two parts. For species which are capable of crossing such a critical distance a larger part of the network is accessible than for species which are not able to cross this distance. The hedgerow network can be described as a graph by representing each of the hedgerows as a point or node, and the possible connections between the hedgerows as lines or edges. Each connection between two hedgerows is weighted by the minimum distance between them. The critical distances in the network can now be determined by calculating a minimum spanning tree (Nešetřil et al., 2001) or the minimum set of edges that connects all parts of the networks.

2.4.2. Landscape character

Landscape character is defined as the presence, variety and arrangement of different landscape features, which gives a landscape a specific identity and makes it stand out from other landscapes (Swanwick and Consultants, 2002). The patterns of fields and hedgerows determine the appearance of the Friesian Woodlands and give a sense of place to the people inhabiting the landscape (Renting and Van Der Ploeg, 2001; Stedman, 2003). Together with LBF the following indicators for variation, continuity and historical characteristics of the hedgerow patterns were developed.

The hedgerows surrounding the fields divide the landscape into elongated visual chambers, the length of which is denoted as sight line (Fig. 2b). Variation in sight lines contributes to the visual quality of the landscape (De la Fuente de Val et al., 2006). Sight line homogeneity, represented by the evenness of the frequency distribution of the length of visual chambers was used as an indicator, and was minimized.

In the hedgerow landscape of the Friesian Woodlands, a sight line from road to road (Fig. 2b) is undesirable and perceived as disturbing the pattern of the landscape. To optimize the continuity of the landscape the indicator porosity, expressed as number of continuous sightlines from road to road, was defined and minimized.

Historically, the landscape has a high ratio of longitudinal hedgerows (L) over transversal hedgerows (T) relative to the parcelling direction, resulting in elongated visual chambers (Anonymous, 2006). This characteristic was maintained by maximizing the L/T ratio.

2.4.3. Implementation and maintenance costs

Removal, planting and maintenance of hedgerows were considered as separate objectives as each is associated with its own ecological, socio-cultural and agronomic considerations which are highly relevant to farmers that invest labour in maintenance and the financers of landscape development plans who would aim to reduce costs of restructuring.

Removal of existing hedgerows can disrupt the socio-cultural characteristics of the landscape expressed in particular patterning. Moreover, older hedgerows, some exceeding 100 years of age, represent unique ecological habitats. And finally, removal of hedgerows is costly. Here, the details of each of these consideration are not taken into account, but as a general objective removal of hedgerows was minimized.

Addition of new hedgerows is also costly and was minimized.

From the perspective of some farmers aiming to develop large-scale farming systems, the presence of hedgerows forms a barrier to manoeuvre with machines and for the enlargement of fields. Moreover, these farmers consider hedgerows as unwanted sinks of labour for maintenance and related costs. To represent this perspective, the total hedgerow length in the landscape was minimized.

2.5. Implementation

The model was implemented in the Microsoft .NET Development Environment. The landscape configuration data were directly accessed from ESRI shape files (Anonymous, 1998) with the ShapeLib.dll (URL: http://www.shapelib.maptools.org/). The addition of new linear landscape elements to the landscape and the removal of landscape elements were determined by the DE algo-

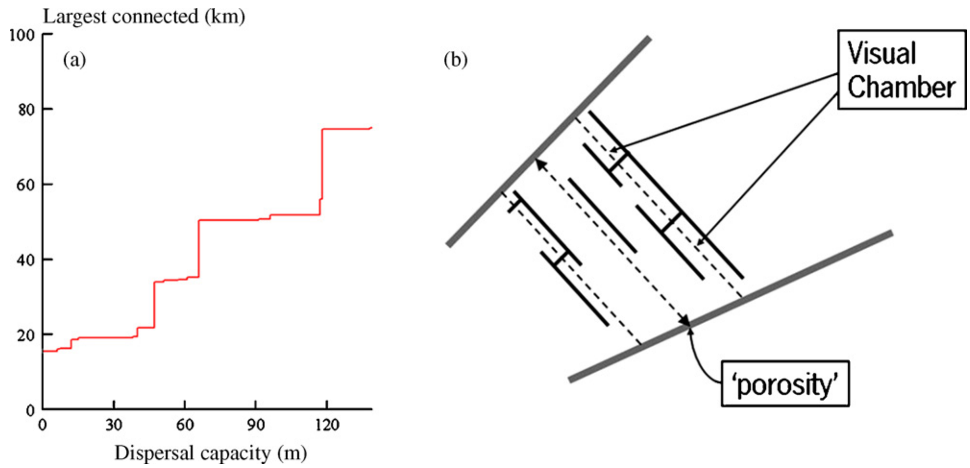

Fig. 2. (a) Spatial coherence of the hedgerow network, defined as the relation between the dispersal capacity (D_{cap}) and the largest interconnected cluster of habitat in the network. The integral of this function was maximized. (b) Conceptual illustration of landscape pattern of the Friesian Woodlands. The hedgerows divide the landscape into elongated visual chambers. Sightlines from road to road (porosity) are undesirable. Legend: ( ) road ( ) hedgerow, and ( ) sightline.

rithm. The generated solutions, each representing a landscape were evaluated for the 7 objectives described above.

3. Results

The final solution set provided by the algorithm offered a large range of Pareto-optimal landscape configurations. The 7-dimensional objective space was visualized by projecting the solutions onto 2-dimensional surfaces (Fig. 3). Relations between some objectives were narrowly defined, e.g. between hedgerow length and spatial cohesion (Fig. 3a) or porosity and sight line homogeneity (Fig. 3p). Apparently the other objectives did not affect the relation in a major way. Such relations indicate strong trade-offs or conflicts between the objectives, leaving limited room for negotiation. At the other extreme, point clouds indicated the existence of alternative Pareto-optimal solutions, e.g. for spatial cohesion and *L*/*T* ratio (Fig. 3g) or for porosity and hedgerows removed (Fig. 3r). For each value of one objective several landscapes existed that were Pareto-optimal, yet very different in terms of the other objective. Such relations provide more room for negotiation. Most relations in Fig. 3 fell between these extremes, combining sharply defined trade-offs with less clear relations.

As an illustration of the interaction among the various indicators, spatial cohesion was found to be positively related to total hedgerow length (Fig. 3a). Alternative solutions at a particular value of total hedgerow length demonstrated that further improvements in spatial cohesion would be possible without increasing total hedgerow length (Fig. 3a) and therefore maintenance costs of hedgerows in the landscape. However, this would involve replacing hedgerows currently positioned in the longitudinal direction of the fields by hedgerows in the transversal direction. As an additional positive effect, such an adjustment would reduce the porosity of the landscape as desired (Fig. 3c), but clear trade-offs existed with other objectives, since the change would probably compromise cultural heritage value as expressed in the *L*/*T* ratio (Fig. 3b), and it would require removal of hedgerows in some places and adding new hedgerows elsewhere in the landscape (Fig. 3e and f). The occurrence of these trade-offs implies that priorities need to be set to make further planning decisions.

We projected the performance of the 'original' landscape configuration (yellow square) and LBFs' 'sketch design' (yellow circle) in the plots describing the solution space (Fig. 3). The decision rules employed by LBF to create the sketch design positively affected spatial cohesion (Fig. 3a) at the cost of adding about 5 km hedgerow and removing none (Fig. 3e and f), but reduced the *L*/*T* ratio from ca. 9 to 6.5. Both porosity and variability in sightlines were slightly increased. LBF did not explicitly evaluate their sketch design for these undesirable changes.

Solutions with a low Pareto efficiency value can be typified as the 'best compromises' because they contain fewer trade-offs and are therefore likely to be interesting from a planner's point of view. Lowest Pareto efficiency found in the set of Pareto-optimal solutions was $k = 5$, which was associated with 5 landscape alternatives (the red circles in Fig. 3). In the solution space these compromise solutions were located close to the original situation, but were characterized by desirable lower sight line homogeneity and higher *L*/*T* ratio, albeit often at the cost of investments in removal and adding of hedgerows. Spatial cohesion remained at a similar level as in the original situation. Solutions with Pareto efficiency values of 6 and 7 were identified in Fig. 3 as blue and green circles, respectively. These points represent solutions in which most trade-offs occur among the 7 objectives, although all are Pareto-optimal.

In Fig. 4 two alternative landscape maps are presented, which constitute the spatial representation of two Pareto-optimal solutions. Although these landscapes have similar economic and ecological performance their visual appearance is very different, which can be related to differences in the values of the indicators of *L*/*T* ratio (8.79 versus 5.75) and landscape porosity (45 versus 15). The presence of different alternative solutions for similar parameter settings demonstrates the various ways in which objectives can be matched and focuses discussion about details of the implementation of a landscape plan.

4. Discussion

Already in the 1970s Penning de Vries (1977) proposed to evaluate model performance in terms of 'usefulness' and 'truthfulness'. Recently, Bockstaller and Girardin (2003) distinguished three validation dimensions, viz. end-user validation equivalent to usefulness, output validation equivalent to truthfulness, and design validation, thus adding the issue of how a particular model configuration or indicator was selected. The latter is particularly relevant where no data exist to assess output validity based on data. We will discuss these three domains in turn starting with end-user validation, leaving aside the philosophical issue of whether 'validation' is possible at all.

The solution space generated by the Landscape IMAGES framework as presented in Fig. 3 revealed the 'playing field' for the NGO

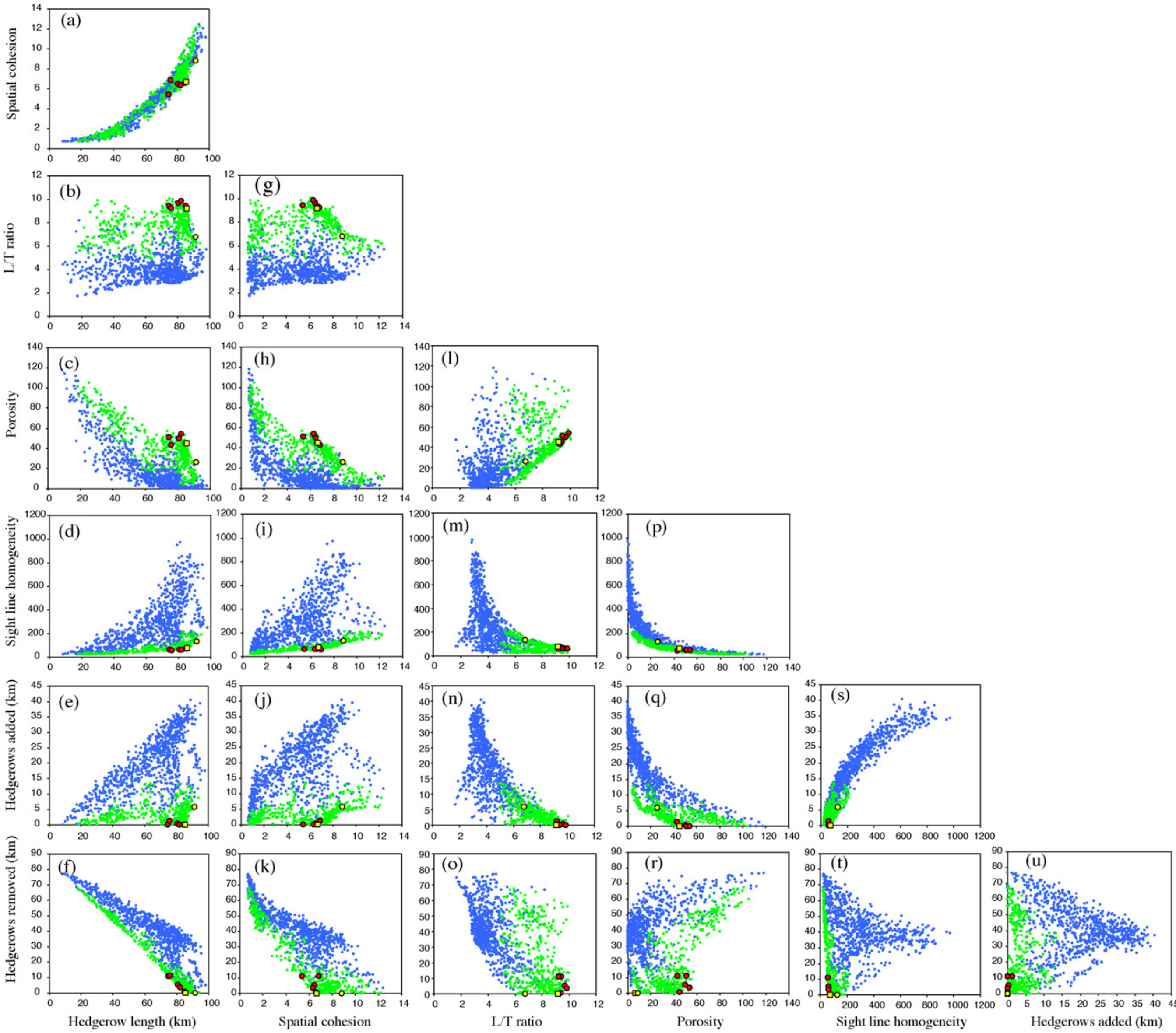

Fig. 3. The 7-dimensional solution space represented by 2-dimensional plots of relations between the objectives. Each point represents a landscape configuration. Symbols indicate Pareto efficiency of $k = 7$ (●, blue), $k = 6$ (●, green) or $k = 5$ (●, red). The original landscape (■ , yellow) and the sketch design developed by the NGO (●, yellow) are indicated.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

'Landschapsbeheer Friesland', as delimited by the minimum and maximum attainable values for the desired objectives; it demonstrated the interactions between objectives including trade-offs and possible synergies; and it provided insight into options to combine different land-use objectives. Such outputs may contribute to the understanding of the system by the stakeholders and can provide a sound basis for balanced decision making that does justice to the perspectives and interests of broad groups of stakeholders, which is considered instrumental for active management of ecosystem services (Robertson and Swinton, 2005).

The study demonstrated that the spatial coherence of the case study area could be increased to support the dispersal opportunities of species with different dispersal ranges, with limited costs of planting of hedgerows or labour inputs of farmers to maintain the hedgerows. Key strategy to achieve such result would be to connect existing large connected fragments of existing hedgerows by targeted placement of new hedgerows in the transversal direction of the fields. This would also reduce the porosity of the landscape, improving the visual perception. On the other hand, it would reduce the ratio between longitudinally and transversally directed hedgerows, thereby changing the cultural heritage value of the landscape. These results originated from a joint effort of researchers and landscape planners. The NGO 'Landschapsbeheer Friesland' considered the application of the Landscape IMAGES framework to be supportive in their landscape re-design practice as was apparent from statements and from their continued participation in the 3-year process. The need in Landscape IMAGES to define explicit objectives and indicators brought out the largely implicit design rules of the NGO and stimulated reflection. Presentation of preliminary results from various intermediate versions of the model during project team meetings helped to elucidate hidden constraints that had been used by the NGO in formulating the sketch design and needed to be included in the model as well. The confrontation between the sketch design and the Pareto optimal set allowed the LBF representatives to assess their result against the range of possible alternatives. The benefit for the NGO end-users was also apparent from their invitation to the research team to contribute to a large landscape restructuring project surrounding the construc-

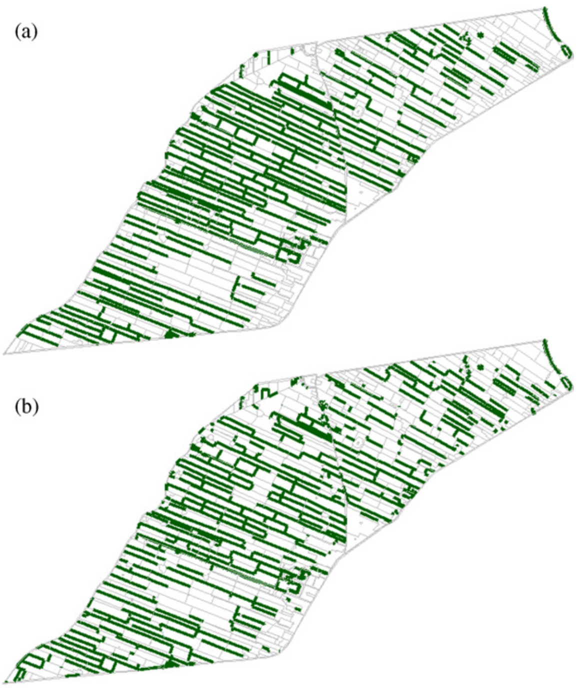

Fig. 4. Original hedgerow configuration in the 873 ha case study region in the Northern Friesian Woodlands (a) and a generated landscape (b) with similar hedgerow length (85.6 km in (a) and 85.7 km in (b)) and connectivity (6.7 and 6.9, respectively), but strongly contrasting ratio between longitudinal and transversal hedges (8.79 in (a) and 5.75 in (b)) and porosity (45 and 15, respectively).

tion of a major road in the area. Here, trade-offs with agriculture will be addressed in more detail.

Output validation concerns the value of the information about reality in the model. No data exist, or are likely to become available soon, about the landscape system as a whole. This implies that validation of the output value shifts to the individual indicators. None of the indicators had a direct link to simulation models, or to a specific dataset. The landscape character indicators porosity, *L*/*T* ratio and sight line homogeneity were strongly based on input by landscape experts from research and from the region. Indicator validity was in these cases thus fully based on consensus, denoted by Bockstaller and Girardin (2003) as global expert validation. The ecological quality indicator landscape cohesion was based on general ecological principles derived from particularly modelling studies (e.g. Urban and Keitt, 2001; Verboom et al., 2001), and thus based on qualitative comparison with results from other approaches (Bockstaller and Girardin, 2003). There is an urgent need for validation based on quantitative tests with empirical data. From the agronomy domain, data and models of gene flow with pollen (Colbach et al., 2009) and dispersal of plant pathogens (Skelsey, 2008) and crop pests (Bianchi et al., 2007) hold promise to better understand the general relation between landscape configuration and distribution patterns.

An important design aspect was the decision to not include agricultural land-use alternatives in the Landscape IMAGES implementation for the NGO. As a consequence, landscape redesign suggestions were not evaluated in terms of pasture management and its consequences to dairy farms operating in the area. The reasons for this were two-fold. Including the large amount of agronomic knowledge on pasture management that is available (e.g. Van de Ven, 1996; Groot et al., 2007; Schils et al., 2007) would obscure model performance on the core interests of the NGO stakeholder and would deviate from the purpose of end-user validation by spatial planners. Secondly, knowledge on the effect of pasture management on the quality of the neighbouring hedgerows or on the potentials for dispersal of organisms is largely absent and so that interactions between landscape and agriculture could not be covered.

Pareto-based Differential Evolution is resilient to different specifications of the optimization problem, which can be easily integrated in a GIS and can be coupled to complex computational algorithms such as mechanistic simulation models and spatial metric calculations, for instance to determine the minimum spanning tree. Mathematical programming methods tend to fall short when faced with large combinatorial problems, as is the case in the applications in this section. Evolutionary computation is a useful compromise for the type of complex decision problems presented here where interest is more in trends and variation in the solutions than in precise optimality. Thus, the flexibility of multi-objective evolutionary computation offers opportunities for connecting different spatial scales as well as different scientific disciplines to create new perspectives for sustainable land-use. Future applications will rely on increased algorithmic efficiency, particularly in view of sparse solution spaces at high numbers of objectives, and techniques to select and present relevant solutions in the discussion and negotiation process.

The results of the three types of validation demonstrate the usefulness of the approach for landscape planning end-users, and the acceptability of the ecological quality and landscape character indicators for experts. The simultaneous analysis of different types of objectives (economic, socio-cultural and ecological), and the scaling up from the field/hedgerow level to the regional level represented new perspectives to the end-users. Visual presentation of trade-offs and the room for negotiation in the various objective dimensions, as well as visualization of the landscapes associated with a certain performance was particularly insightful for the end-users. The study also suggests that to contribute to this type of spatial planning agronomic research should invest in understanding consequences of land-use for spatial coherence. This will support the ambitions of an increasing number of European farmers to contribute to multifunctionality for the benefit of society at large. The Landscape IMAGES model may play a role as a tool for integration of knowledge when used in a process with end-users that allows joint construction of the various components of the model, including objectives, system definition and performance indicators. As witnessed in the case study, the model then represents the boundary object in which progress in mutual understanding materializes, which constitutes a key element for end-user validity (Sterk et al., 2006).

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References

Anonymous, 1998. ESRI Shapefile Technical Description. Environmental Systems Research Institute, Redlands, CA, USA, p. 34.
Anonymous, 2006. Nota Ruimte. Ruimte voor ontwikkeling. Ministry of Health, Spatial Planning and Environment, Den Haag.
Baudry, J., Bunce, R.G.H., Burel, F., 2001. Hedgerows: an international perspective on their origin, function and management. J. Environ. Manage. 60, 7–22.
Bergey, P.K., Ragsdale, C., 2005. Modified differential evolution: a greedy random strategy for genetic recombination. Omega-Int. J. Manage. Sci. 33, 255–265.
Bianchi, F.J.J.A., Honěk, A., van der Werf, W., 2007. Changes in agricultural land use can explain population decline in a ladybeetle species in the Czech Republic: evidence from a process-based spatially explicit model. Landsc. Ecol. 21, 1541–1554.
Bockstaller, C., Girardin, P., 2003. How to validate environmental indicators. Agric. Syst. 76, 639–653.
Bondy, J.A., Murty, U.S.R., 1977. Graph Theory with Applications. American Elsevier Publishing Co., New York, p. 270.
Bryan, B.A., Crossman, N.D., 2008. Systematic regional planning for multiple objective natural resource management. J. Environ. Manage. 88, 1175–1189.

Carpenter, S.R., DeFries, R., Dietz, T., Mooney, H.A., Polasky, S., Reid, W.V., Scholes, R.J., 2006. Millennium ecosystem assessment: research needs. Science 314, 257–258.

Chee, Y.E., 2004. An ecological perspective on the valuation of ecosystem services. Biol. Conserv. 120, 549–565.

Colbach, N., Devaux, C., Angevin, F., 2009. Comparative study of the efficiency of buffer zones and harvest discarding on gene flow containment in oilseed rape. A modelling approach. Eur. J. Agronomy 30, 187–198.

Cumming, G.S., Cumming, D.H.M., Redman, C.L., 2006. Scale mismatches in social-ecological systems: causes, consequences, and solutions. Ecol. Soc., 11.

Das, I., 1999. A preference ordering among various Pareto optimal alternatives. Struct. Opt. 18, 30–35.

De Boer, J.J., 2003. Veldgids landschapselementen Noardlike Fryske Walden. Stichting Landschapsbeheer Friesland, Beetsterzwaag, 196 pp.

De la Fuente de Val, G., Atauri, J.A., de Lucio, J.V., 2006. Relationship between landscape visual attributes and spatial pattern indices: a test study in Mediterranean-climate landscapes. Landscape Urban Plan. 77, 393–407.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE T. Evol. Comput. 6, 182–197.

Dijkstra, H., Bianchi, F.J.J.A., Griffioen, A.J., Van Langevelde, F., 2003. Typering van landscapeseenheden in Nederland naar groen-blauwe dooradering. Alterra-rapport 645, Alterra, Wageningen, pp. 79.

Dockerty, T., Lovett, A., Appleton, K., Bone, A., Sünnenberg, G., 2006. Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes. Agric. Ecosyst. Environ. 114, 102–120.

Fall, A., Fortin, M.J., Manseau, M., O'Brien, D., 2007. Spatial graphs: principles and applications for habitat connectivity. Ecosystems 10, 448–461.

Franks, J.R., Mc Gloin, A., 2007. Environmental co-operatives as instruments for delivering across-farm environmental and rural policy objectives: lessons for the UK. J. Rural Stud. 23, 472–489.

Goldberg, D.E., 1989. Genetic algorithms in search. In: Optimization and Machine Learning. Addison-Wesley, Reading, p. 412.

Gottfried, R., Wear, D., Lee, R., 1996. Institutional solutions to market failure on the landscape scale. Ecol. Econ. 18, 133–140.

Groot, J.C.J., Rossing, W.A.H., Jellema, A., Stobbelaar, D.J., Renting, H., Van Ittersum, M.K., 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—a methodology to support discussions on land-use perspectives. Agric. Ecosyst. Environ. 120, 58–69.

Groot, J.C.J., Rossing, W.A.H., Tichit, M., Turpin, N., Baudry, J., Jellema, A., Doyen, L., Van de Ven, G.W.J., 2009. On the contribution of modelling to multifunctional agriculture: learning from comparisons. J. Environ. Manage. 90, S147–S160.

Hajkowicz, S., Perraud, J.M., Dawes, W., DeRose, R., 2005. The strategic landscape investment model: a tool for mapping optimal environmental expenditure. Environ. Model. Softw. 20, 1251–1262.

Holloway, L., Cox, R., Venn, L., Kneafsey, M., Dowler, E., Tuomainen, H., 2006. Managing sustainable farmed landscape through 'alternative' food networks: a case study from Italy. Geo. J. 172, 219–229.

Hölzkamper, A., Seppelt, R., 2007. A generic tool for optimising land-use patterns and landscape structures. Environ. Model. Softw. 22, 1801–1804.

IAASTD, 2008. Agriculture at a crossroads: the synthesis report. Washington, DC, USA: International Knowledge, Science and Technology for Development. www.agassessment.org/.

Kangas, J., Store, R., Kangas, A., 2005. Socioecological landscape planning approach and multicriteria acceptability analysis in multiple-purpose forest management. Forest Policy Econ. 7, 603–614.

Leenhardt, D., Angevin, F., Biarnès, A., Colbach, N., Mignolet, C., 2009. Describing and locating cropping systems on a regional scale. A review. Agron. Sustain. Dev., doi:10.1051/agro/2009002.

Mayer, D.G., Kinghorn, B.P., Archer, A.A., 2005. Differential Evolution – an easy and efficient evolutionary algorithm for model optimization. Agric. Syst. 83, 315–328.

Münier, B., Birr-Pedersen, K., Schou, J.S., 2004. Combined ecological and economic modelling in agricultural land use scenarios. Ecol. Model. 174, 5–18.

Nešetřil, J., Milková, E., Nešetřilová, H., 2001. Otakar Borůka on minimum spanning tree problem: translation of both the 1926 papers, comments, history. Discrete Math. 233, 3–36.

O' Conner, D., Renting, H., Gorman, M., Kinsella, J., 2006. Driving Rural Development: Policy and Practice in Seven EU Countries. Van Gorcum Publishers.

Otte, A., Simmering, D., Wolters, V., 2007. Biodiversity at the landscape level: recent concepts and perspectives for multifunctional land use. Landsc. Ecol. 22, 639–642.

Penning de Vries, F.W.T., 1977. Evaluation of simulation models in agriculture and biology: conclusions of a workshop. Agric. Syst. 2, 99–107.

Renting, H., Rossing, W.A.H., Groot, J.C.J., Van der Ploeg, J.D., Laurent, C., Perraud, D., Stobbelaar, D.J., Van Ittersum, M.K., 2009. Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. J. Environ. Manage. 90, S112–S123.

Renting, H., Van Der Ploeg, J.D., 2001. Reconnecting nature, farming and society: environmental cooperatives in The Netherlands as institutional arrangements for creating coherence. J. Environ. Pol. Plan. 3, 85–101.

Robertson, G.P., Swinton, S.M., 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Front. Ecol. Environ. 3, 38–46.

Rossing, W.A.H., Zander, P., Josien, E., Groot, J.C.J., Meyer, B., Knierim, A., 2007. Integrative modelling approaches for analysis of impact of multifunctional agriculture: a review for France, Germany and the Netherlands. Agric. Ecosyst. Environ. 120, 41–57.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C., Zom, R.L.G., 2007. DairyWise, a whole-farm dairy model. J. Dairy Sci. 90, 5334–5346.

Skelsey, P., 2008. Multi-scale modeling of potato late blight epidemics. PhD Thesis Wageningen University, Wageningen, pp. 257.

Stedman, R.C., 2003. Is it really just a social construction? The contribution of the physical environment to sense of place. Soc. Nat. Resour. 16, 671–685.

Sterk, B., van Ittersum, M.K., Leeuwis, C., Rossing, W.A.H., van Keulen, H., van de Ven, G.W.J., 2006. Finding niches for whole-farm design models—contradictio in terminis? Agric. Syst. 87, 211–228.

Storn, R., Price, K., 1997. Differential evolution—a simple and efficient heuristic for global optimization over continuous spaces. J. Global Optim. 11, 341–359.

Swanwick, C., Consultants, L.U., 2002. Landscape Character Assessment—Guidance for England and Scotland. Countryside Agency, Cheltenham and Scottish Natural Heritage, Edinburgh.

Swetnam, R.D., Wilson, J.D., Whittingham, M.J., Grice, P.V., 2005. Designing lowland landscape for farmland birds: scenario testing with GIS. Comput. Environ. Urban Syst. 29, 275–296.

Tichit, M., Doyen, L., Lemel, J.Y., Renault, O., Durant, D., 2007. A co-viability model of grazing and bird community management in farmland. Ecol. Model. 206, 277–293.

Urban, D., Keitt, T., 2001. Landscape connectivity: a graph-theoretic perspective. Ecology 82, 1205–1218.

Van de Ven, G.W.J., 1996. A mathematical approach to comparing environmental and economic goals in dairy farming on sandy soils in The Netherlands. PhD Thesis, Wageningen University, 239pp.

Verboom, J., Foppen, R., Chardon, P., Opdam, P., Luttikhuizen, P., 2001. Introducing the key patch approach for habitat networks with persistent populations: an example for marshland birds. Biol. Conserv. 100, 89–101.

Vos, W., Meekes, H., 1999. Trends in European cultural landscape development: perspectives for a sustainable future. Landsc. Urban Plan. 46 (1–3), 3–14.